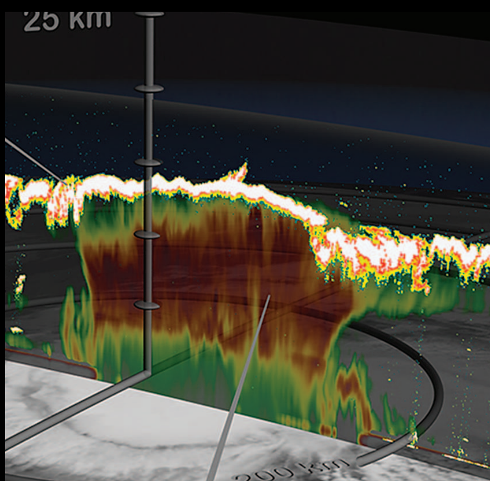
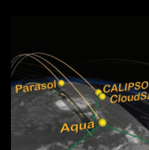
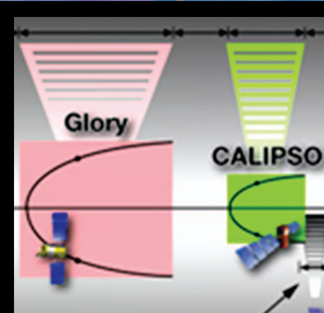
National Aeronautics and
Space Administration

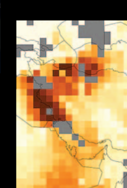
The A-Train

Formation Flying for Understanding Earth









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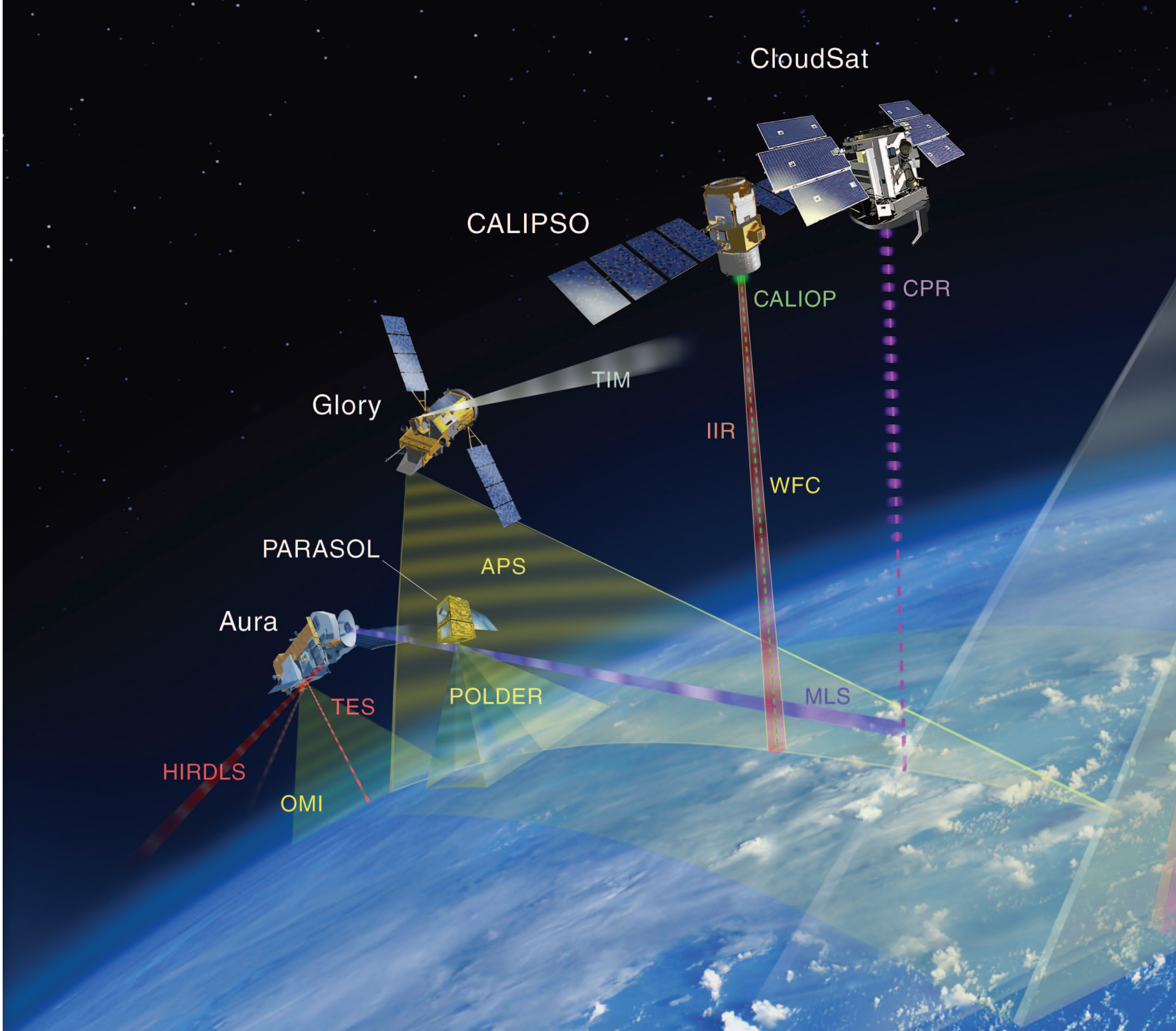
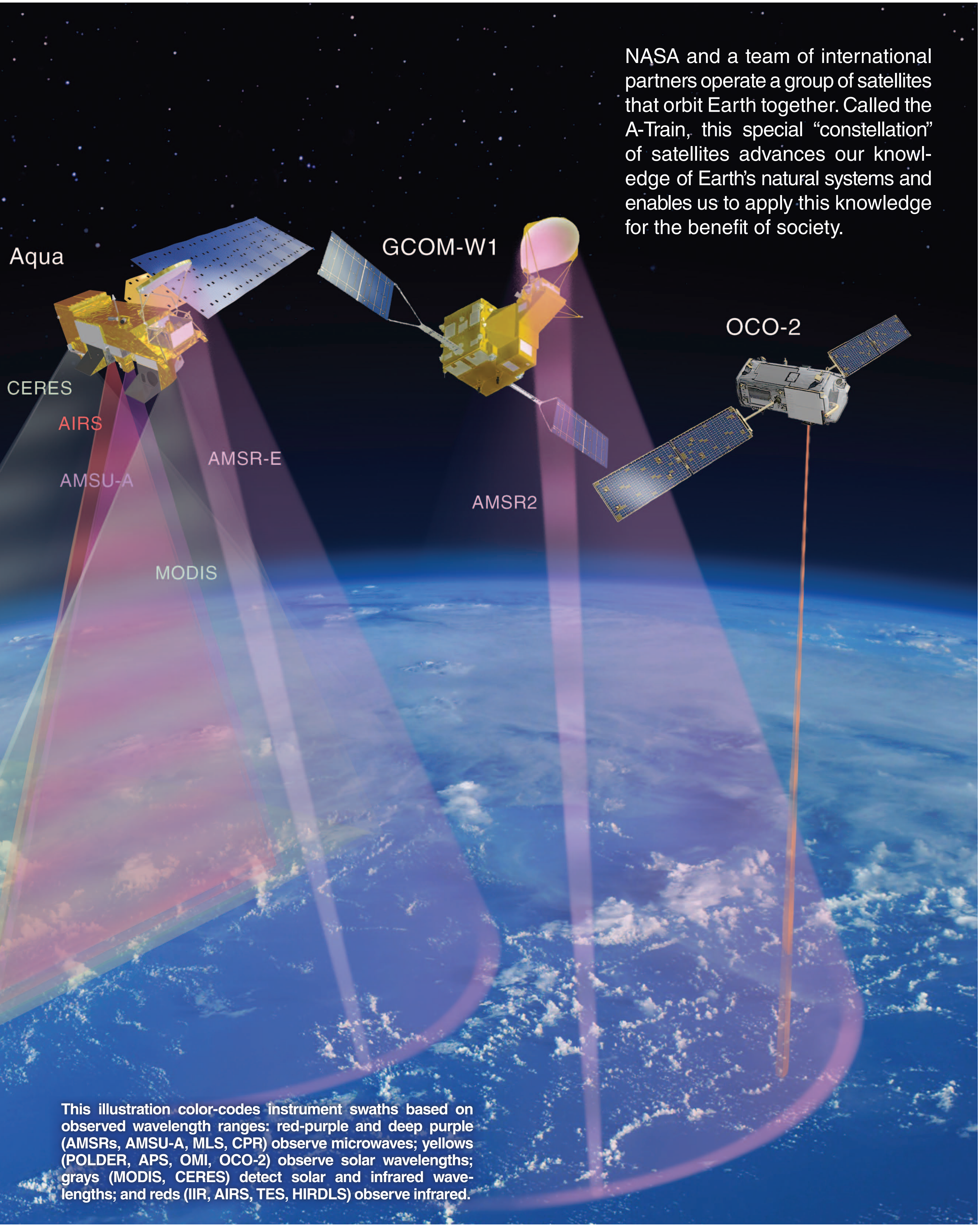
The changing Earth environment is increasingly a focus of many agricultural, industrial, and societal concerns. To effectively respond to these issues, policy makers must have access to timely and accurate information about the Earth system.



As depicted here, by about 2014, the international Afternoon Constellation should include OCO-2, GCOM-W1, Aqua, CloudSat, CALIPSO, Glory, and Aura. In December 2009, PARASOL began to leave the formation; it will exit completely by 2012, with Glory taking over its position. The instruments on these precisely engineered satellites make almost simultaneous measurements of clouds, aerosols, atmospheric chemistry, and other elements critical to understanding Earth's changing climate. The footprint of each of the A-Train's instruments is shown; active instruments aboard CALIPSO (CALIOP) and CloudSat (CPR) are indicated with dashed lines.

NASA and a team of international partners operate a group of satellites that orbit Earth together. Called the A-Train, this special “constellation” of satellites advances our knowledge of Earth’s natural systems and enables us to apply this knowledge for the benefit of society.



This illustration color-codes instrument swaths based on observed wavelength ranges: red-purple and deep purple (AMSRs, AMSU-A, MLS, CPR) observe microwaves; yellows (POLDER, APS, OMI, OCO-2) observe solar wavelengths; grays (MODIS, CERES) detect solar and infrared wavelengths; and reds (IIR, AIRS, TES, HIRDLS) observe infrared.

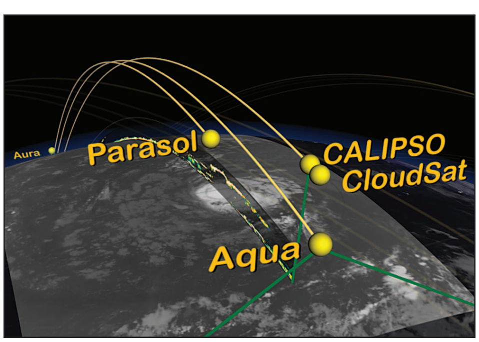
What is the A-Train?

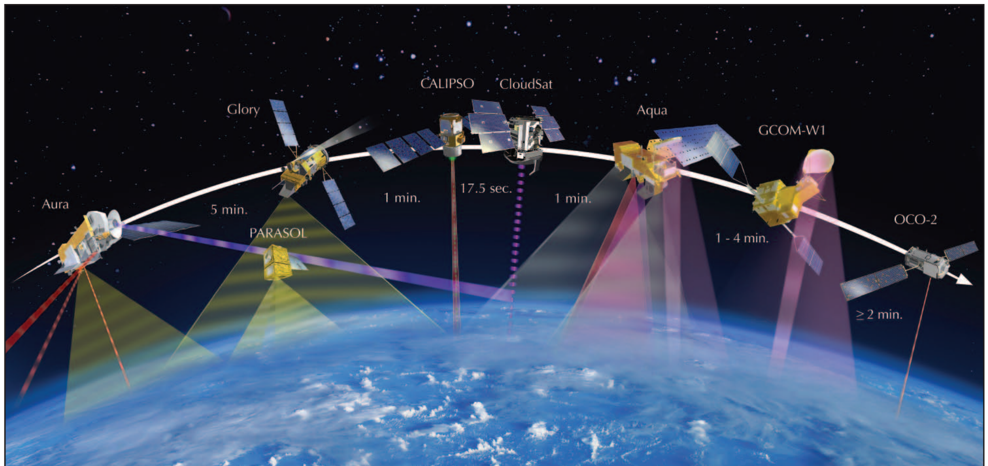
NASA and its international partners operate a group of Earth-observing satellites that closely follow one after another along the same orbital "track." This coordinated set of satellites, constituting a significant subset of NASA's current operating major satellite missions, is called the *Afternoon Constellation*, or the *A-Train*, for short.

A-Train's satellites follow a polar orbit, crossing the equator at about 1:30 p.m. local time within seconds to minutes of each other (see illustration at right). This configuration allows practically simultaneous observations of a wide variety of parameters to aid the scientific community in advancing our knowledge of Earth-system science.

The analogy of a train isn't perfect for a group of Earth-observing satellites orbiting in space. Each satellite is able to function and collect data completely independently of all the others and has an independent mission to fulfill. While they aren't literally connected like railroad cars, precise engineering and planning—called formation flying—allows for them to function as if they were "connected."

Formation flying enables the instruments aboard all the A-Train satellites to operate together almost as if they were on the same platform. This means that scientists can use instruments on several different satellites in the constellation to study particular atmospheric phenomena—e.g., clouds, aerosols, greenhouse gases—and learn more than they could have with any one satellite by itself.





The A-Train is displayed here with all seven satellites in its planned configuration (by about 2014), with PARASOL drifting out of the A-Train completely by 2012. This image shows the amount of time each spacecraft is separated along the group's orbit track. In this diagram, the constellation is traveling from left to right in its south-to-north polar orbit.

The Satellites

At the present time, the A-Train consists of four NASA missions and a French Centre National d'Etudes Spatiales (CNES) mission flying in close proximity to one another. The NASA missions are: Aqua (launched in 2002), Aura (launched in 2004), the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) and CloudSat (both launched together in 2006), and the French satellite mission, Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL, launched in 2005). As of December 2, 2009, PARASOL began a slow exit from the A-Train. It will drift completely out of the formation by the end of 2012. Plans are in progress to "expand" the A-Train to allow for even more comprehensive studies of Earth's processes and climate.

Glory will join the A-Train no sooner than the end of 2010, filling the position previously occupied by PARASOL. Glory will measure solar energy entering our atmosphere to determine its long-term effects on Earth's climate record and to collect data on the properties of natural and human-caused aerosols as agents of climate change in Earth's atmosphere.

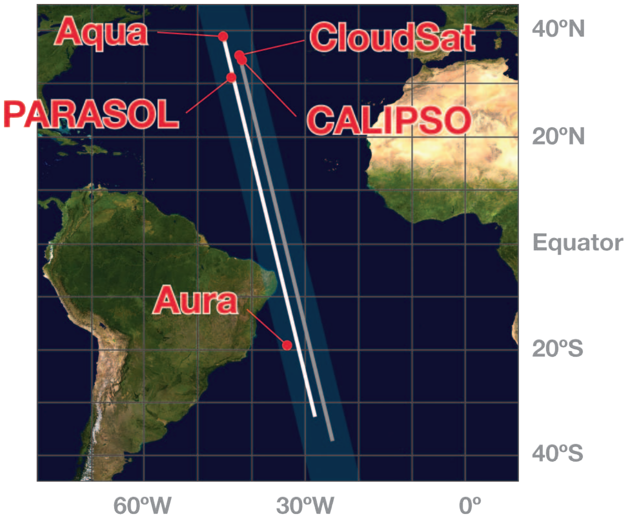
The Global Change Observation Mission (GCOM-W1), a mission from the Japan Aerospace Exploration Agency (JAXA), is scheduled to join the A-Train in early 2012. A second-generation Advanced Microwave Scanning Radiometer (AMSR2) will observe atmospheric and oceanic parameters (precipitation, sea surface temperature and wind speed, cloud liquid water, and column water vapor), sea ice concentrations and snow water equivalent, and surface wetness over land.

The second Orbiting Carbon Observatory (OCO-2) satellite will join the configuration in early 2013. It is NASA's first satellite dedicated to making full-column measurements of carbon dioxide (CO_2) with the sensitivity, resolution, and coverage needed to quantify surface sources and sinks of this important greenhouse gas.

Combining data from these satellites enables scientists to gain a better understanding of a variety of Earth-system processes including those relevant to climate. Information collected simultaneously gives a more complete answer to important science questions than would be possible with the same satellite data collected at different times.

Flying in Formation

The A-Train is more than several satellites following each other in orbit. In order for multiple instruments to observe the same cloud, those instruments must be sufficiently close together so that they can view the cloud within a brief amount of time or else the cloud will have changed. [Read more in the sidebar, "Taking in the View"] Satellites that carry these in-



The figure above shows A-Train's satellites in orbit. Here, the satellites are traveling south to north, from the bottom to the top of the illustration.

struments must, therefore, fly closely together in a carefully planned and executed formation.

Horizontal separation is one important aspect of formation flying. Presently, the first four A-Train satellites—Aqua, CloudSat, CALIPSO, PARASOL—fly in tight formation, so they can view the same locations from above within a brief time span.

CALIPSO is sensitive to sun glint and is therefore positioned to avoid this phenomenon. The satellite is 215 km to the side of Aqua's orbit that faces away from the sun and must not lag Aqua by more than two minutes or may never precede it. CloudSat has to maneuver in tandem with CALIPSO to maintain position relative to Aqua and also maneuvers independently to preserve its position no more than 15 seconds ahead of CALIPSO. Aura is positioned substantially behind the others, so its Microwave Limb Sounder (MLS) can view horizontally the same portion of the atmosphere that Aqua is viewing from above.

There is a remarkable advantage to this precise formation—at the expense of a slight time separation, formation flying simulates a satellite that is hundreds of kilometers in size!

Formation Flying:
A Control Issue

The A-Train is a carefully planned formation that allows for *synergy* between the missions. Synergy means that more information about the condition of Earth is obtained from combined observations than would be possible from the sum of the observations taken independently.

However, in order for synergistic measurements to be successfully obtained, the formation has to be precisely aligned. This calls for coordinated maneuvering of the various spacecraft to keep them in a tight formation.

The heart of formation flying is *control boxes*. Each satellite is allowed to drift within its respective control box (seen as colored boxes surrounding the satellites in the diagram below) until it approaches the boundary of the box. At that point the satellite must execute maneuvers to adjust its orbit. These maneuvers maintain the observing times and geometries of the instruments, but more importantly, they avoid collisions, which would threaten the entire formation by producing a debris field.

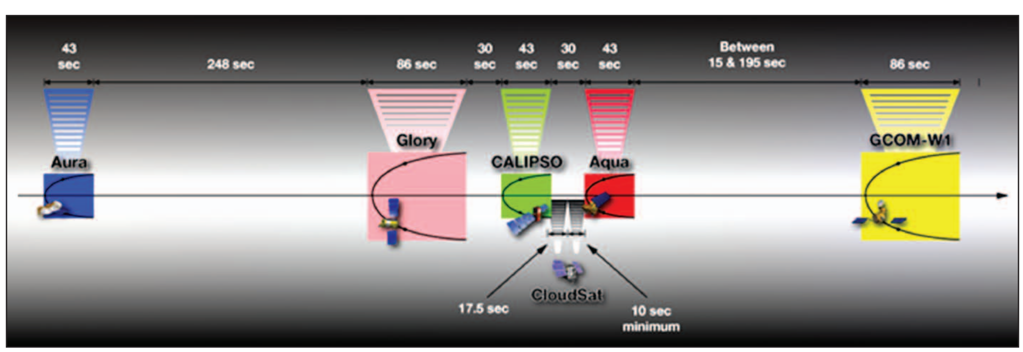
In the current A-Train configuration, Aqua is maintained inside a control box of 21.5 seconds (about ±158 km). It makes precisely 233 complete orbits in 16 days. CloudSat flies in a mini-formation 12.5±2.5 seconds ahead of CALIPSO. CALIPSO is maintained in a ±21.5 second control box averaging 73 seconds, or about 547 km, behind Aqua, meaning it's never closer than 30 seconds (or 225 km) to Aqua. Similarly, PARASOL flew about 131 seconds behind Aqua. And, finally, Aura flies about 900 seconds behind Aqua.

Seeing the World with Different Glasses

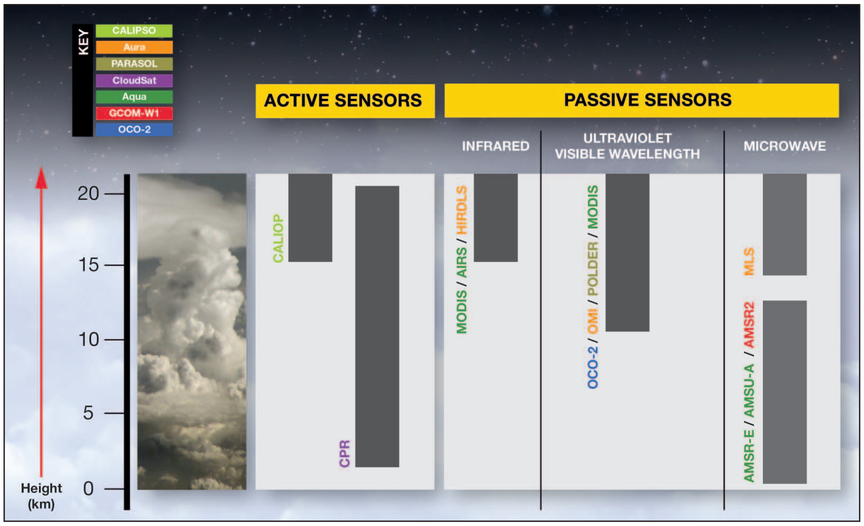
Some A-Train sensors have a larger *footprint*—scanning a much larger spatial area than others. Some have higher *resolution*—they can "see" the target in greater detail than others. The illustration top right highlights the difference in the way the A-Train sensors observe clouds.

The *active sensors* (i.e., CPR and CALIOP) emit "pencil-thin" pulses of energy that slice through the atmosphere, and strike a target. The *return pulse* of energy is analyzed to produce a very high-resolution view of a very small area. For CALIOP the pulse is visible light, which is very sensitive to aerosol layers and high, thin clouds, but can't penetrate the atmosphere when thicker clouds are present. For CPR, the pulse is microwave energy, which can easily penetrate lower and thicker clouds and is sensitive to 90% of all clouds.

The *passive sensors* don't emit energy; they "see" reflected sunlight in the visible and ultraviolet wavelengths, and heat (infrared) that is both reflected and emitted from Earth's atmosphere and surface. They provide wider, more global coverage, allowing for snapshots of different layers of the atmosphere. Each instrument detects



Control boxes are crucial to the success of the A-Train. Each mission must stay within a tightly defined area and execute periodic maneuvers to maintain its position in the formation.



The A-Train is equipped with a variety of *passive* and *active* remote-sensing instruments. This diagram shows the differences in how individual satellite sensors are able to penetrate through Earth's atmosphere.

certain wavelengths of infrared, visible, ultraviolet, or microwave energy. It turns out that each of these types of radiation offers strengths and weaknesses when it comes to observing the atmosphere. Infrared (IR) sensors detect the heat released from whatever "surface" they observe, but can't penetrate thick cloud layers. (HIRDLS is an *infrared limb sounder* that looks sideways across the atmosphere and is more sensitive to very high, thin clouds.) Ultraviolet and visible sensors (e.g., MODIS) are able to probe deeper into clouds than IR sensors, but not all the way to the surface. Microwave sensors (e.g., AMSR/AMSU) can "see" the whole atmosphere—even when it's cloudy. (MLS is a bit different; it is a limb sounder that looks across the atmosphere and detects frozen water in the tops of towering clouds.)

The challenges of combining the measurements are considerable, but when all these perspectives are successfully brought together, what emerges is one of the most complete pictures of the Earth system ever obtained. This new information is helping to improve our understanding of the individual elements that compose the Earth system and how these elements interact to influence Earth's climate.

A-Train Data Depot and ICARE

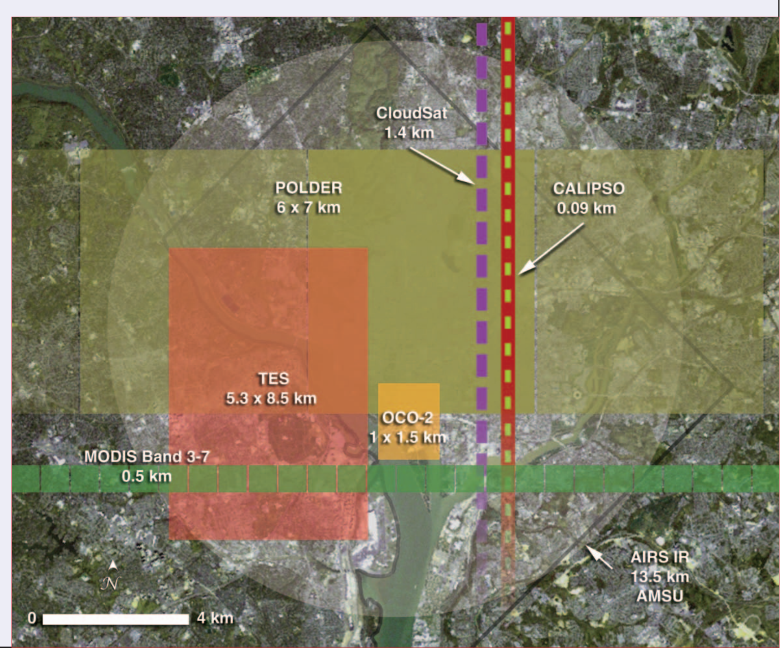
Each A-Train instrument team has an established infrastructure for data production, archiving, and distribution of Level-1 and higher-order products.

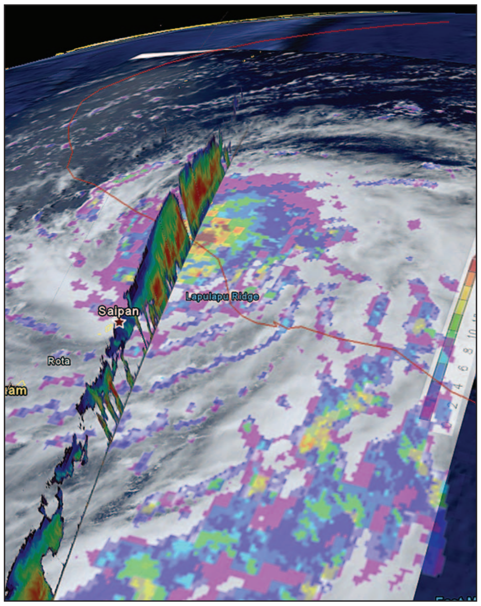
Taking in the View

The two illustrations shown here illustrate a few of the different A-Train instrument footprints and also highlight the challenge of formation flying discussed earlier.

The map at left shows a view of the current A-Train satellites as if looking down on the entire constellation from orbit. The satellites that make up the A-Train travel from south to north (bottom to top in this image). The satellites near the front of the A-Train—i.e., Aqua, CloudSat, CALIPSO, PARASOL—are positioned in a close grouping (top), while Aura brings up the rear of the constellation, and is positioned much further back (bottom). The colorful bars across each satellite illustrate the scanning swath of several instruments. From this more remote perspective, the instruments with smaller footprints are barely visible. The table in this illustration lists each satellite, selected instruments, and the width of each swath in kilometers.

The image at right shows the overlapping footprints of several of A-Train instruments (colors correspond to the table above) superimposed on a close-up image of Washington, DC. The purpose is to give a sense of how, over the course of an orbit, the swath of each instrument overlaps the others, allowing for the nearly simultaneous observations of the same location or event that are crucial to the science of the A-Train. This close-up perspective also brings the challenge of formation flying into sharper focus. In order to successfully overlap science measurements from different A-Train instruments, each with varying footprints and resolutions, each member of the A-Train must strictly maintain its position in the constellation as described above.





The A-Train flew over the super-typhoon Choi-wan on September 15, 2009. This particular image includes data from four A-Train sensors: CPR (CloudSat), MLS (Aura), MODIS, and AMSR-E (Aqua). The potential for scientific discovery dramatically increases when the A-Train's diverse sensors observe the same phenomena at virtually the same time.

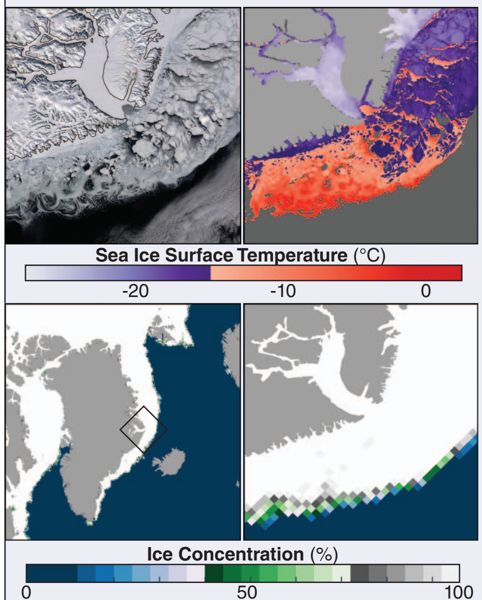
Details are available at the mission and instrument web sites. In addition, cross-instrument A-Train data distribution systems, including merged (collocated) data and visualization capabilities, have been developed as described below.

The A-Train Data Depot (ATDD) has been developed to process, archive, allow access to, visualize, analyze, and correlate distributed atmospheric measurements from A-Train instruments. The portal provides easy on-line data access and services for science, applications, and educational use so that users get exactly the data they want, and not large files of data which would take much time and effort by individuals to be co-registered and refined.

The ICARE Thematic Center was created in 2003 by CNES, the Centre National de la Recherche Scientifique (CNRS), the Nord-Pas-De-Calais Regional Council, and the University of Lille, to provide various services to support the research community in fields related to atmospheric research, such as aerosols, clouds, radiation, the water cycle, and their interactions.

Stories from the A-Train

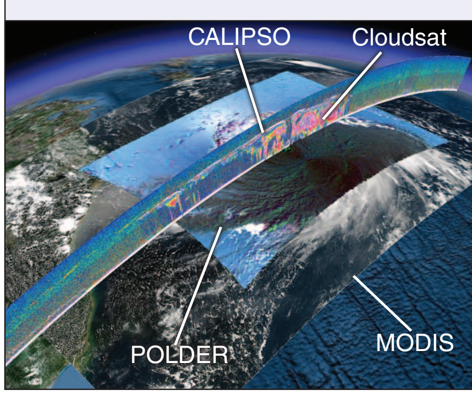
Sea Ice



Images of East Greenland, above, show sea ice for March 27, 2010 from the Aqua satellite. A true-color MODIS image (upper left) shows glacier- and snow-covered land and individual sea ice floes in the ocean. Lower ice-surface temperature (IST) derived from MODIS (upper right) is evident near the coast (purple) where sea ice concentration is also high (AMSR-E image, lower right), with increasingly higher ISTs toward the sea ice-open water boundary where the IST shows melting and the ice concentration goes to zero. In addition, IST decreases northward and roughly in concert with increasing sea ice concentration, though not apparent in this image.

Hurricane Bill

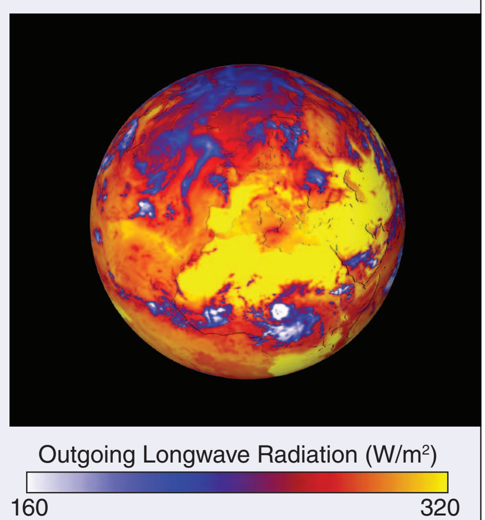
An image of Hurricane Bill as seen from the MODIS instrument (flying on Aqua) along with the cloud vertical distribution observed from the CALIOP lidar (CALIPSO) and CloudSat radar on August 19, 2009. Superimposed on the MODIS image is the polarized reflected sunlight observed by POLDER (PARASOL); the relatively dark polarization signal indicate clouds comprised of ice particles (cold, higher clouds) while the brighter scenes indicate liquid water clouds.



Merging together the diverse perspectives of the various A-Train instruments allows scientists to begin to observe the structure and dynamics of hurricanes and tropical storms in three dimensions and gives us much more information about their structure to help improve forecasts of their track and intensity.

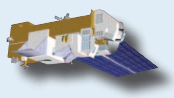
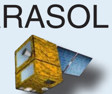
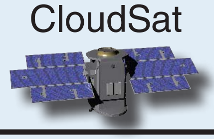
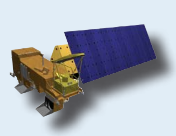
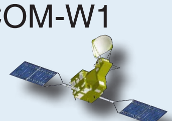
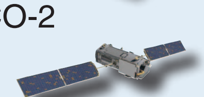
Heatwave

The globe below shows outgoing longwave (infrared) radiation emitted by the Earth and atmosphere during the European heatwave of 2003, as determined from the CERES instrument on Aqua. The blue-to-white colors represent very cold (high-altitude) clouds, while the yellow colors represent the warmest scenes corresponding to the largest outgoing infrared energy. The CERES calculations make use of aerosol and cloud retrievals from MODIS and therefore the radiation budget calculations are being informed by CALIPSO and CloudSat observations.



The A-Train's instruments (shown below) work together to produce a comprehensive picture of the Earth system. Most are *passive* instruments that detect radiation emitted or reflected from a target. Each instrument detects radiation in one or more *spectral bands*—a range of microwave, infrared, visible, or ultraviolet wavelengths. The bands are relatively broad for imaging instruments as compared to the extremely narrow bands of several thermal infrared instruments. The instruments cover a variety of different viewing angles and *polarizations*—that only allow light of certain wavelengths oriented in a certain direction to pass.

In contrast, CloudSat's radar and CALIPSO's lidar are *active* instruments that emit an energy pulse (microwave and visible radiation, respectively) and measure the energy reflected or backscattered to the sensor. Scientists study these *return pulses* and use them to create three-dimensional profiles of clouds and aerosols.

Satellite	Instrument		Measurement
Aura 	HIRDLS	High Resolution Dynamics Limb Sounder	Temperature and composition of the upper troposphere, stratosphere, and mesosphere; aerosol extinction and cloud height
	MLS	Microwave Limb Sounder	Temperature and composition of the upper troposphere and stratosphere; upper tropospheric cloud ice
	OMI	Ozone Monitoring Instrument	Total column ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, bromine monoxide, aerosol absorption, and cloud centroid pressure
	TES	Tropospheric Emission Spectrometer	Temperature, ozone, carbon monoxide, and water vapor profiles from the surface to the lower stratosphere
PARASOL 	POLDER	POLarization and Directionality of the Earth's Reflectances	Polarized light measurements of clouds and aerosols
Glory 	APS	Aerosol Polarimetry Sensor	Visible, near-infrared, and short-wave infrared data scattered from aerosols and clouds
	CC	Cloud Camera Sensor Package	Continuous cross-track coverage over a field of view centered on the APS along-track footprint
	TIM	Total Irradiance Monitor	Total solar irradiance with extreme accuracy and precision
CALIPSO 	CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization	High-resolution vertical profiles of aerosols and clouds
	IIR	Imaging Infrared Radiometer	Nadir-viewing, non-scanning imager
	WFC	Wide Field Camera	Fixed, nadir-viewing imager with a single spectral channel covering a portion of the visible (620–670 nm) region of the spectrum to match Band 1 of the MODIS instrument on Aqua
CloudSat 	CPR	Cloud Profiling Radar	Vertical profiles of water amount measured by backscattered radar signals from clouds
Aqua 	AIRS	Atmospheric Infrared Sounder	Highly accurate temperature profiles within the atmosphere
	AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observing System (EOS)	Precipitation rate, cloud water, water vapor, sea-surface winds, sea-surface temperature, ice, snow, and soil moisture
	AMSU-A	Advanced Microwave Sounding Unit-A	Temperature profiles in the upper atmosphere, especially in the stratosphere
	CERES	Cloud's and the Earth's Radiant Energy System	Solar-reflected and Earth-emitted radiation; cloud properties (altitude, thickness, and size of the cloud particles)
	HSB	Humidity Sounder for Brazil	Humidity profiles throughout the atmosphere **(Inoperative)**
	MODIS	MODerate-resolution Imaging Spectroradiometer	Vegetation, land surface cover, ocean chlorophyll fluorescence, cloud and aerosol properties, fire occurrence, land snow cover, and sea ice cover
GCOM-W1 	AMSR2	Advanced Microwave Scanning Radiometer, 2nd generation	Enhanced understanding of water in Earth's climate system and the global water cycle, and of additional components of Earth's climate system and their interactions
OCO-2 	Three high-resolution grating spectrometers		Full-column measurements of CO_2

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